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Article

Tracking Environmental Compliance and Remediation Trajectories Using Image-Based Anomaly Detection Methodologies

James K. Lein

Department of Geography, Ohio University, Athens, OH 45701, USA; E-Mail: lein@ohio.edu; Tel.: +1-740-593-1147; Fax: +1-740-593-1139

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Abstract: Recent interest in use of satellite remote sensing for environmental compliance and remediation assessment has been heightened by growing policy requirements and the need to provide more rapid and efficient monitoring and enforcement mechanisms. However, remote sensing solutions are attractive only to the extent that they can deliver environmentally relevant information in a meaningful and time-sensitive manner. Unfortunately, the extent to which satellite-based remote sensing satisfies the demands for compliance and remediation assessment under the conditions of an actual environmental accident or calamity has not been well documented. In this study a remote sensing solution to the problem of site remediation and environmental compliance assessment was introduced based on the use of the RDX anomaly detection algorithm and vegetation indices developed from the Tasseled Cap Transform. Results of this analysis illustrate how the use of standard vegetation transforms, integrated into an anomaly detection strategy, enable the time-sequenced tracking of site remediation progress. Based on these results credible evidence can be produced to support compliance evaluation and remediation assessment following major environmental disasters.

Keywords: environmental compliance; remediation; anomaly detection; vegetation transform

1. Introduction

Interest in the application of satellite-based remote sensing technologies for environmental compliance and remediation assessment has been heightened by a continuing need to ameliorate the impact of human activities on critical environmental resources [1,2]. Environmental compliance and remediation efforts however are activities guided by regulatory instruments that function in a highly time-dependant manner. These policy efforts are also strongly influenced and directed by the activities and operations they are designed to police. Determining whether or not the status of a specific human construction or land use enterprise complies with a set of design or operational behaviors or whether landscape elements damaged by human actions have been repaired to a less impacted and more sustainable state is challenging [1]. The environmental system is complex and equally complex are the practical constraints that frustrate enforcement protection [3]. The obstacles introduced by uneven enforcement and inspection philosophies, together with the personnel and budgetary reductions that plague environmental protection programs, encourages novel solutions to augment or replace deficient physical inspection regimes [4].

Remote sensing solutions become attractive in this context only to the extent that they can deliver environmentally relevant information and provide a mechanism that supports meaningful oversight in a time-sensitive manner [5]. Although research has shown that remote sensing technologies have tremendous potential for compliance and remediation applications, this potential has only been demonstrated in a "proof-of-concept" manner [2,4]. Precisely how well satellite-based remote sensing satisfies the demands for compliance and remediation assessment under the conditions of an actual environmental accident or calamity has not been well documented. In this paper the application of satellite-based remote sensing in post-calamity remediation and compliance role is examined. Drawing on the experience of the Kirby Tire fire that occurred on 21 August 1999 near Sycamore, Ohio, the event-driven research described in this paper evaluates the feasibility of employing moderate resolution Landsat TM data for anomaly detection and site remediation monitoring. Through the use of standard vegetation transforms integrated into an anomaly detection strategy, credible evidence was derived that support time-sequenced tracking of site remediation progress and the identification of "off-site" impacts related to the fire event and subsequent "clean-up" operations.

2. Compliance Monitoring and Site Remediation

Human activities prone to promote environmental damage or threaten environmental quality are often the target of policy instruments designed to regulate their scope and mitigate their adverse consequences [6]. A critical element of many environment policy directives and protection strategies are the enforcement mechanisms introduced to insure regulatory compliance. For the purposes of this study, environmental compliance may be defined as the state of being in accordance with a set of guidelines, specifications or legislative mandates designed to protect or manage environmental resources or amenities [7-9]. The enforcement and systematic review of actions known to damage the environmental system, however, is fraught with complications and constraints that limit serious attempts to engage in comprehensive assessments [2,10]. Site remediation refers to the restoration of a contaminated site to a condition that is no longer considered a threat to human health or other forms of life. Typically, remediation activities focus largely on the removal of contaminants from environmental media such as soil, groundwater, sediment, or surface waters. As a form of environmental restoration, remediation may be targeted toward the general protection of human health, or the closure of highly contaminated areas and their isolation from the rest of the environmental system. Similar to the question of environmental compliance, site remediation is generally subject to an array of regulatory requirements, Remediation goals may also be based on more general assessments of human health and ecological risks, particularly in situations where legislative standards are absent or where standards are advisory.

Achieving compliance and identifying situations where actions or activities fail to agree with established standards remains a vital aspect of environmental protection. Therefore developing an effective environmental compliance program is an essential ingredient to any successful public or private sector entity whose activities impinge on the environment [11]. Equally critical are the questions of enforcement and the capabilities of governmental agencies to systematically monitor an organization's operational behavior with respect to environmental process. While environmental laws that have formed the basis for a system of environmental regulation have been in existence for over three decades, the broad system of environmental regulation is complex and obtaining a comprehensive understanding is often confounded by periodic statutory amendments, new laws and on-going modifications to existing regulations [6]. Consequently, both compliance and site remediation begin with an evaluation of environmental requirements together with a review of the applicable laws and regulations that govern the activity in question.

Generally, compliance and remediation inspections rely heavily on field-based inspections by regional or state-level staff as the primary means of detecting violations and evaluating overall progress [2]. The effectiveness of enforcement based on this model varies with the quality and content of these inspections and the number of inspections undertaken to provide adequate coverage. For example, within US, the US General Accounting Office (GAO) found that United States Environmental Protection Agency regions vary substantially in the actions taken to enforce environmental regulations [12]. This analysis found that most of the variability in enforcement could be attributed to three main factors:

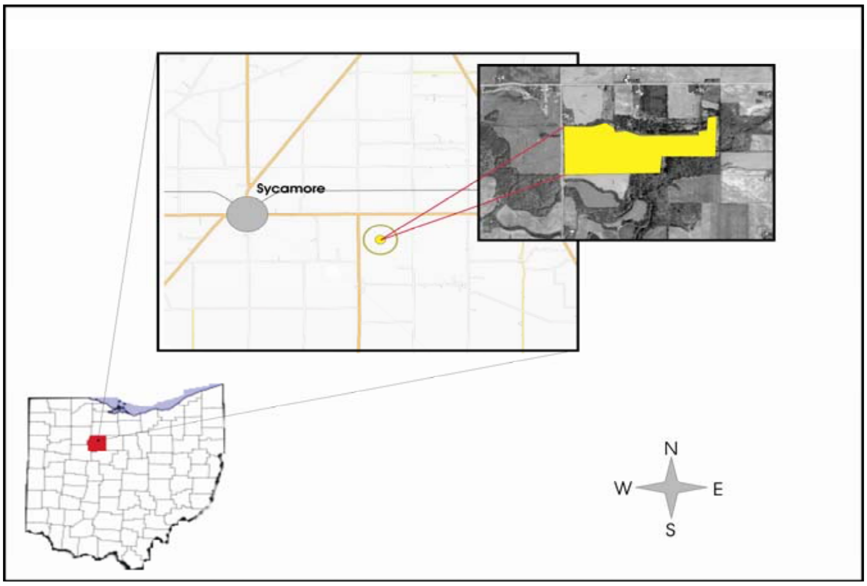
- Differences in the philosophy of enforcement staff about how to best achieve compliance relative to environmental requirements
- Incomplete and inadequate enforcement data, and
- Antiquated workforce planning systems that hampered enforcement consistency and effectiveness.

3. The Kirby Event

At 2:00 am on 21 August 1999 a fire was discovered at the Kirby tire recycling facility near Sycamore, Ohio (Figure 1). Twenty local fire departments along with 34 residents of the area responded and the United States Environmental Protection Agency assume control of response activities by mid-morning of that day. The Kirby tire recycling facility opened in the early 1950's and periodic attempts to close or limit the size of tire pile followed soon after. In 1993 the Wyandot County Board of Health ordered removal of the tires which was followed in 1997, a court order to remove the tires from the site. Failure to remove the tires led to contempt charges in 1998 and later that year the tire recycling facility was ordered to cease the acceptance of scrap tires altogether. The State of Ohio began removing tires from the site in July of 1999, approximately one month prior to the arson set fire.

At the time of the fire the 140 acre Kirby tire recycling site contained approximate 25 million Passenger Tire Equivalents (PTE's) with piles ranging from 40 to 60 feet in height, 200 feet in width and 1,000 feet in length. The fire itself consumed 14 acres of the site and burned for 30 hours. Preliminary site remediation required 5 days to cover the burning tires with soil and an additional 19 days to complete a one foot clay cover over the burn area.

Figure 1. Study Area location and regional setting.



Within four days following the fire, discharge from the site into Sycamore Creek resulted in a complete fish kill which adversely impacted all 7.5 miles of the stream. Five years following the calamity 1.99 million gallons of water had been treated and 200 gallons of oil created from the burning tires had been recovered. Total remediation operations however required nine years as a cost exceeding 32 million dollars (US) [13-15].

4. Methodology

To facilitate environmental monitoring and to gain a full appreciation of the contribution moderate resolution satellite imagery brings to the question of compliance and remediation assessment, analysis was conducted under the guiding assumption that this study began on 21 August 1999. Adopting this unique temporal perspective to assess compliance and remediation progress for the Kirby site is an attempt to frame the scenario of the present looking forward with uncertainty rather than the more typical "post-mortem" perspective of the past looking back in time with complete knowledge. This assumption guided all aspects of the methodology, underscoring the sense of urgency that would follow an environmental calamity and the decisions that would have been required in order to respond to the event in "real-time". Three key decision points frame the method according to the "real-time" response scenario: (1) Data Acquisition, (2) Environmental Site Characterization, (3) Temporal Monitoring and Assessment.

4.1. Data Acquisition

The Kirby fire occurred on 21 August 1999 and a search for moderate resolution Landsat TM imagery was undertaken to identify a Landsat overpass date closest to the fire event. Two dates were noted, 17 August 1999 (pre-fire) and 2 September 1999 (11 days post-event). The 17 August scene was acquired for Path 19, Row 32 that defined the location of Sycamore, Ohio and the Kirby site (40°56′39.03″N, 83°07′31.85″W). A spatial subset of the Kirby site and surrounding area was made which was converted to radiance values following a dark object subtraction. All subsequent scenes in the time sequence would be subject to the same pre-processing and calibration procedures and geometrically registered to the 17 August subset image (Figure 2).

Figure 2. General methodology used in the analysis.

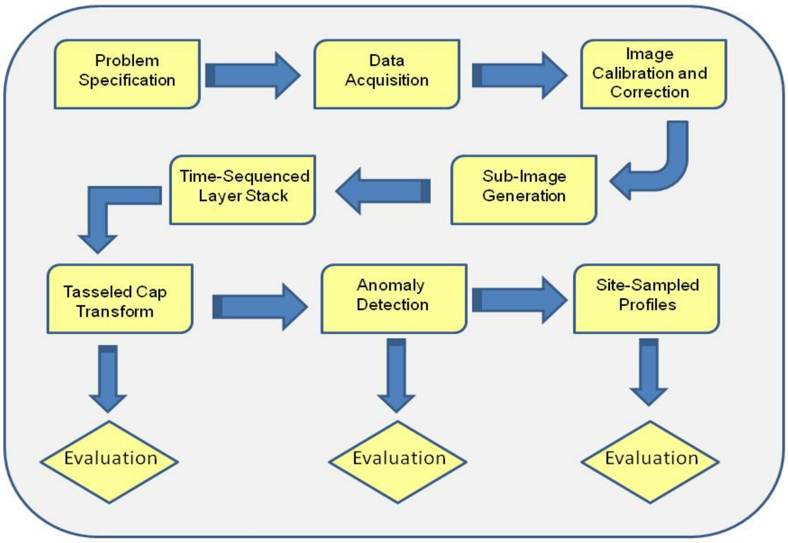


Table 1. Image data set used in the analysis.

Date	Path	Row	Scene ID
30 August 1998	19	32	L519032_03219980830
17 August 1999	19	32	L519032_03219990817
2 September 1999	19	32	L519032_03219990902
18 September 1999	19	32	L519032_03219990918
6 August 2001	19	32	L519032_03220010806
13 September 2003	19	32	L519032_03220030913
10 September 2005	19	32	L519032_200522910
4 August 2006	19	32	L519032_2006_0804
23 August 2007	19	32	L519032_03220070823
19 September 2009	19	32	L519032_03220090913

Continuing with the implied requirements of environmental monitoring, anniversary scenes were collected based on the 21 August reference date. The use of anniversary scene insured that landscape illumination and related environmental characteristics would be comparatively constant so that any observed deviations detected from year to year could be attributed to human activities at the site indicative on remediation procedures and the environmental response to rehabilitation efforts. Ten scenes formed the time sequence with gaps in the series explaining images where cloud cover obscured the site and precluded selection of a suitable anniversary date (Table 1). The assembled imagery, all accessed via the Glovis visualization server (http://glovis.usgs.gov), formed the data set that would result from an annual evaluation and assessment of the impacted site and its affected environment.

4.2. Environment Site Characterization

Characterizing the site and surrounding environmental situation in a manner that supported environmental impact assessment required the selection of an indicator that could synthesize a range of environmental conditions at a given point in time and could be employed to describe year to year progressions in site conditions following a monitoring strategy [16]. An environmental monitoring strategy that facilitates compliance and remediation assessment directs attention to seven practical issues that also help refine how remote sensing technology is applied;

1. **Definition of Objectives**—the basic question to resolve pertains to how one determines which aspects of the environmental system are to be assessed and how in this process change is to be defined and expressed.
2. **Indicator Selection**—based on the stated objectives and which characteristics provide the most concise and relevant answer to the monitoring question,
3. **Method**—what is the optimal means for measuring and observing the indicator,
4. **Measurement Frequency**—what is the temporal interval needed to identify meaningful environmental trends, yet infrequent enough not to saturate the process with data overload,
5. **Program Assessment**—as monitoring ensues, on-going assessment of the objectives, indicator measurement frequency and methods of analysis are required to insure consistency and validity of results,
6. **Data Analysis**—what methods enable the assessment and analysis of change and which offer the greatest capacity to explore trends in the data,
7. **Evaluation**—as information is acquired from the monitoring program, how well does it support decision needs.

4.2.1. The Tasseled Cap Indicator

Environmental indicators are instruments designed to quickly and easily inform a target audience about the status of an object of interest [4]. When abstracted from remotely sensed data, indicators serve to communicate information about environmental conditions and, over time, about significant changes and trends that are actively reshaping the landscape. Communication is perhaps the most important function of an indicator and to be effective in this role, an indicator should enable or promote information exchange regarding the characteristics it has been designed to address [17]. In relation to the goals of environmental compliance and remediation, indicators serve three critical functions:

1. They supply information on the status and condition of the environment
2. They support management and policy decision making, and

3. They facilitate monitoring of critical environmental thresholds.

Of the available image-derived indicators of environmental conditions, the Kauth-Thomas Tasseled Cap Transform was selected for this application [18,19]. The Tasseled Cap transformation is one of the available methods for enhancing spectral information content of Landsat TM data. The Tasseled-Cap Transformation is a conversion of the original bands of an image into a new set of bands with defined interpretations that are useful for vegetation assessment. The first tasseled-cap band corresponds to the overall brightness of the image. The second tasseled-cap band corresponds to "greenness" and is typically used as an index of photosynthetically-active vegetation. The third tasseled-cap band is often interpreted as an index of "wetness" (e.g., soil or surface moisture) or "yellowness" (e.g., amount of dead/dried vegetation) (Table 2).

Table 2. General features of the Tasseled Cap transform.

Transform Band	Band Description
1	Brightness, measure of soil
2	Greenness, measure of vegetation
3	Wetness, interrelationship of soil and canopy moisture

A tasseled-cap transform is performed by taking "linear combinations" of the original image bands Tasseled Cap index was calculated from data of the related six TM bands. The Tasseled Cap Transformation for Landsat satellite imagery is typically calculated according to the formula:

$$\text{Brightness} = 0.3037(TM1) + 0.2793(TM2) + 0.4743(TM3) + 0.5585(TM4) + 0.5082(TM5) + 0.1863(TM7)$$

$$\text{Greenness} = -0.2848(TM1) - 0.2435(TM2) - 0.5436(TM3) + 0.7243(TM4) + 0.0840(TM5) - 0.1800(TM7)$$

$$\text{Wetness} = 0.1509(TM1) + 0.1973(TM2) + 0.3279(TM3) + 0.3406(TM4) - 0.7112(TM5) - 0.4572(TM7).$$

Tasseled cap results and change in tasseled cap values between images will be used to assess changes to the environment in response to both the impact of the fire event and site remediation activities.

4.3. Temporal Monitoring and Assessment

When conducting studies of the environmental system we conveniently assume the surface is in an ambient state, where objects that form the landscape of interest organize into what we define as an expected condition. The synoptic view provided by our imagery gives us a spatial perspective where our expectations of "normal" conditions support certain beliefs regarding how the processes constituting the environmental system perform [20]. Image-derived indicators not only document the ambient state of the environment, but also to communicate curious, conspicuous, and unanticipated patterns that emerge from an otherwise homogeneous background. This form of detection highlights the presence of anomalies at the surface and enables their evaluation and spatial representation. With specific reference to environment compliance and remediation, an anomaly can be defined as a deviation or departure from the normal or expected pattern of a key indicator. Such deviations, when detected, emerge from the background as peculiar, irregular, abnormal and therefore difficult to classify. Anomaly detection attempts to locate and identify irregular or abnormal patterns at the surface based on the image. A surface anomaly can be explained as any pixel that is spectrally different when compared to its background. Conceptually, we can visualize anomalous pixels as spikes or troughs in brightness values whose unique characteristics cannot be attributed to noise or error. Distinctiveness, however, relies on statistical measures that separate difference by applying anomaly thresholds to the imagery.

Using the convention of a threshold, pixels can be extracted from the background pattern thereby reducing the likelihood of returning false positives. Conducted in this manner, anomaly detection can be an important component of environmental characterization and monitoring programs, since it is the irregularities and departures from expected conditions that signal reason for concern. While intuitively appealing, the challenge with anomaly detection relates to identification of "extreme" or "out of place" pixels in the digital imagery. Because anomalous pixels do not conform to expected values, outlier detection is concerned with changes in an image over time or delineating regions within a static scene that appear abnormal. The anomaly can therefore be spatial or temporal taking the form as outlying points in the data distribution

Algorithms utilizing multiple bands locate anomalies (outliers) that are essentially very bright or very dark according to their relative location in multi-spectral measurement space [21]. For the purposed of this study the detection of indicator anomalies relied on the use of the R(x) algorithm developed by Reed and Yu. [22] The basic R(x) algorithm is defined according to the equation:

$$\Omega_{RDX}(\, r\,) = (\, r - \text{ж})^T \times K_{L \times L} \times (\, r - u\,)$$

where r is the vector of pixel spectral values, ж is the mean spectral vector for the area of interest (the mean of each spectral band), L is the number of spectral band, u is the sample mean, and K is the spectral covariance matrix. The algorithm performs in a manner similar to how a human analyst would visually search or outliers in a single band image by identifying bright or dark pixels. The form of RXD(**r**) is actually the well known Mahalanobis distance. However, from a detection point of view, the use of $K_{L \times L}$ can be interpreted as a whitening process to suppress image background. A human analyst would, of course, be challenged to identify outliers simultaneously across several spectral bands, the R(x) algorithm; however, by implementing the Mahalanobis distance formula, the algorithm establishes a multivariate search space that facilitates detection using either multi- or hyper-spectral data [19].

5. Site Remediation and Rehabilitation Tracking

The primary objective of this study was to evaluate the feasibility of employing moderate resolution Landsat TM data for anomaly detection and site remediation monitoring. Two focusing questions framed the analysis:

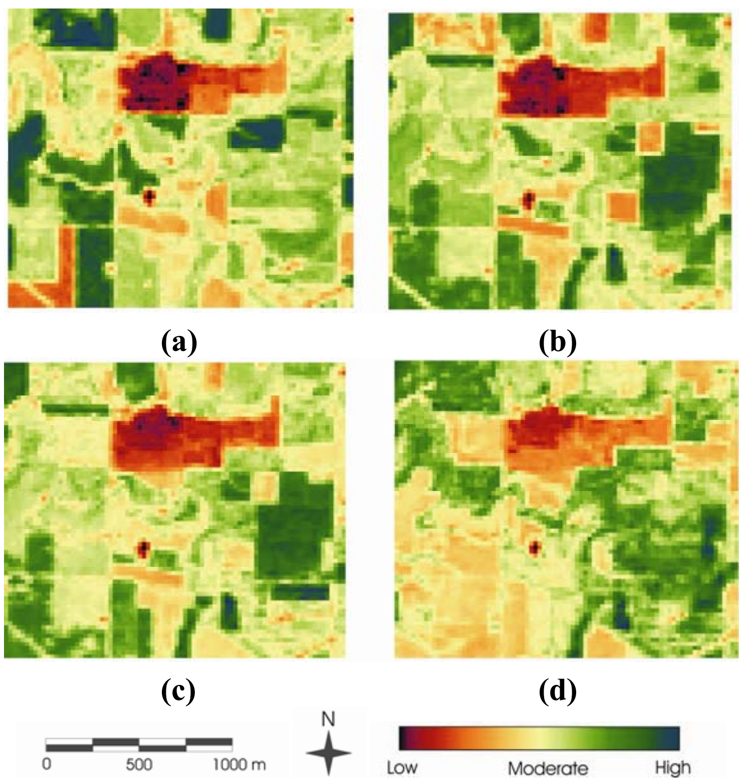
(1) Is moderate resolution imagery sufficient to capture subtle trends in environmental impacts related to human disturbances, and
(2) Can moderate resolution imagery provide meaningful information to support review and evaluation of compliance and site remediation programs?

Analysis proceeded in three phases. Initially the greenness index derived via the tasseled cap transform was examined across the time horizon not to detect change in greenness but rather to define the sequential pattern of greenness from date to date. The second phase of analysis concentrated on the detection of surface anomalies in the combined brightness, greenness, and wetness indices produced from the tasseled cap transformation. The final phase of analysis concentrated on site-specific sampling of greenness and surface anomalies in and around the impacted area to examine localized pre-disturbance and post-disturbance trends and to evaluate remediation trajectories.

5.1. The Greenness Trajectory

The pre- and post-event patterns in greenness are illustrated in Figures 3 and 4. Recalling that the Tasseled Cap transform is essentially a principal components analysis of the input Landsat TM scene, brightness represents the vector depicting the magnitude of reflected energy particularly related to soils, greenness represents an orthogonal plane that contains all of the information pertaining to vegetation, characterizing variations in the vigor of green vegetation, while wetness (yellowness) defines a plane orthogonal to both brightness and greenness defined by atmospheric haze and senescent vegetation. Tracking greenness provided a reasonable means to examine the extent to which the tire fire event and its related consequence adversely impacted agricultural and riparian communities and offered an indicator that was sensitive site rehabilitation strategies. Two pre-event images, one depicting the landscape one year prior to the disturbance (30 August 1998) and the second, four days prior to the calamity (17 August 1999) (Figure 3(a,b)) clearly illustrate the rectilinear outline of the 140 acre Kirby tire recycling facility and the concentration of tires at the western portion of the property. Vegetation patterns surrounding the facility show comparative strong vegetation signals indicative of the active agricultural activities that are prominent in the vicinity. The post-disturbance impact is captured on the next two images in the series 2 September 1999, 12 days following the calamity (Figure 3(c)) and 18 September 1999, 28 days following the calamity (Figure 3(d)).

Figure 3. Greenness index characterization time sequence pre and immediate post event: **(a)** 30 August 1998, **(b)** 17 August 1999, **(c)** 2 September 1999 and **(d)** 18 September 1999.



Runoff from the site carried pyrolytic oil which flowed to the immediate west and south of the facility. The effects of that flow are evident in the post-disturbance images in a declining vegetation signal that persisted through to the first anniversary image indicating cessation of cropping activity within the fields adjacent to the facility due to soil contamination (Figure 4(a)). The 2003 image (Figure 4(b)) describe improved condition to the west of the facility but persistent vegetation decline to the south proximate to the Sycamore Creek riparian corridor. Improvement in the status of the surrounding environment can be observed in the 2005 image (Figure 4(c)) particularly to the west and south where the vegetation signal display a heightened pattern of vigor and the emergence of re-establishing site conditions (Figure 4(d)). The final three images in the series characterize site improvements and the general rehabilitation of the facility (Figure 5(a,b)). At each step in this sequence the site appears to contract as barren soil and sparsely reseeded land moderates the emerging vegetation signal.

Figure 4. Greenness index characterization time sequence continued: **(a)** 6 August 2001 **(b)** 13 September 2003, **(c)** 10 September 2005, **(d)** 4 August 2006.

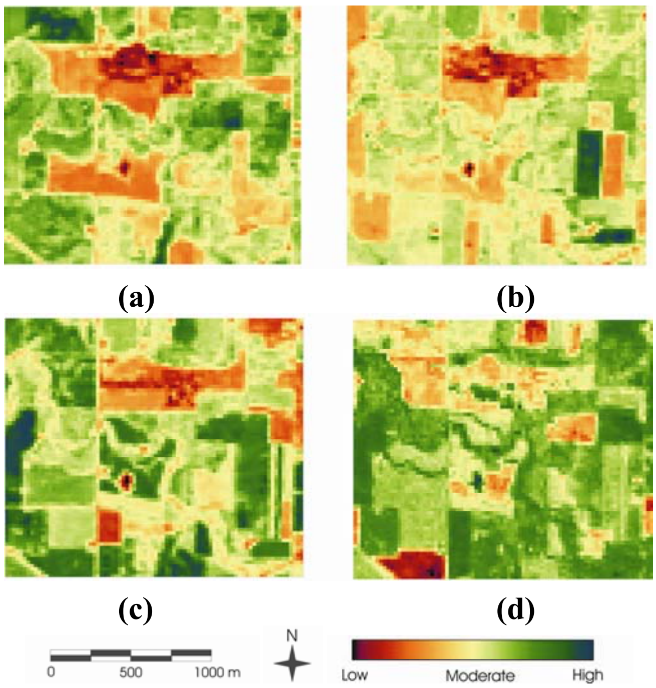
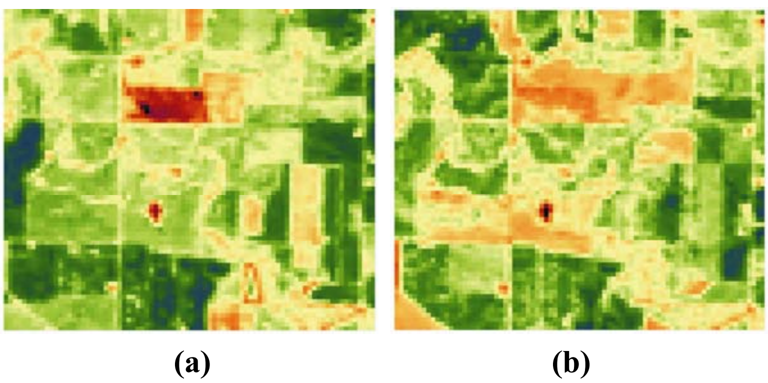


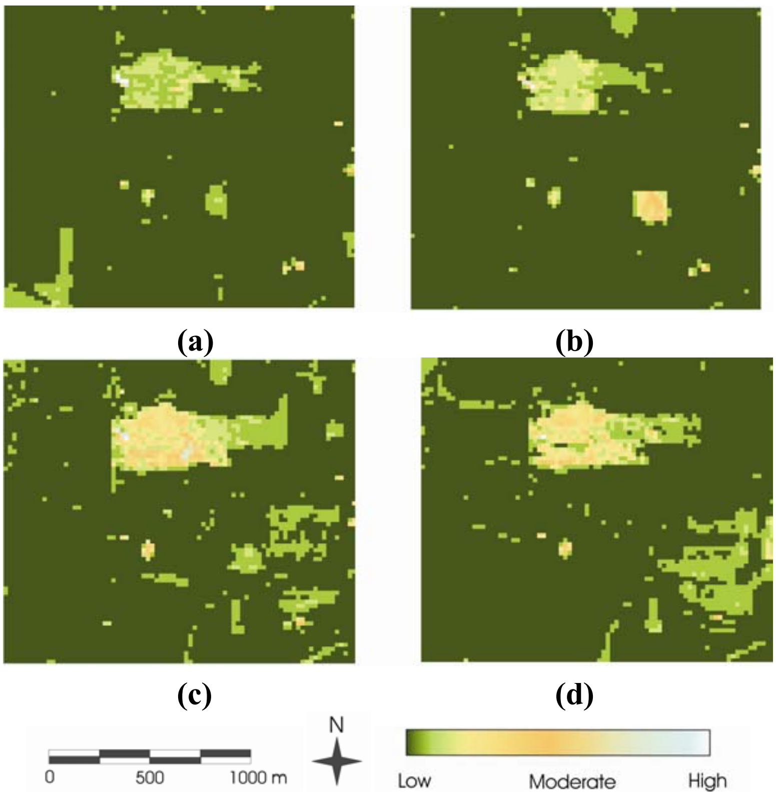
Figure 5. Greenness index characterization time sequence continued: **(a)** 23 August 2007, **(b)** 19 September 2009.



5.2. The Anomaly Trajectory

Anomaly detection employed the RXD anomaly detection algorithm in its classic form to extract anomalous features from the tasseled cap data. The algorithm extracts targets that are spectrally distinct from the image background, highlighting pixels that are different from the general image. Using this algorithm, subtle contrasts in brightness, greenness and yellowness features could be detected that could potentially signal areas slow to recover from the disturbance or locations where outlier conditions persist in the landscape. As illustrated in Figure 6(a,b), "outlier" pixels are confined primarily to the tire recycling facility and the pattern of anomaly intensities in both post-disturbance images (Figure 6(c,d)). Off site anomalies do not appear immediately but can be seen in the first anniversary image (Figure 6(d)) to the south of the tire recycling facility.

Figure 6. Characterization of surface vegetation anomaly patterns: **(a)** 30 August 1998, **(b)** 17 August 1999, **(c)** 2 September 1999, **(d)** 18 September 1999.



Although anomaly detection does not appear sensitive to the impacts generated by the contaminated runoff, it does provide useful insight into the pace of site remediation. As shown in Figure 7(a–d), the presence of outlier pixels declines as site rehabilitation involving the removal of buried tires and the replacement of soil contributed to the contraction of impacted landscape and the return of comparatively homogeneous conditions. However, it must be recognized that active site remediation can at times produce discontinuities in the pattern as soil removal, reseeding, and ground preparations generate short-term effects. At the conclusion of the series low to moderate patterns dominate as the impacted site blends into the background, reducing the sharp delineation that outlined the facility in previous scenes (Figure 8(b)).

Figure 7. Characterization of surface vegetation anomaly patterns continued: **(a)** 6 August 2001, **(b)** 13 September 2003, **(c)** 10 September 2005 and **(d)** 4 August 2006.

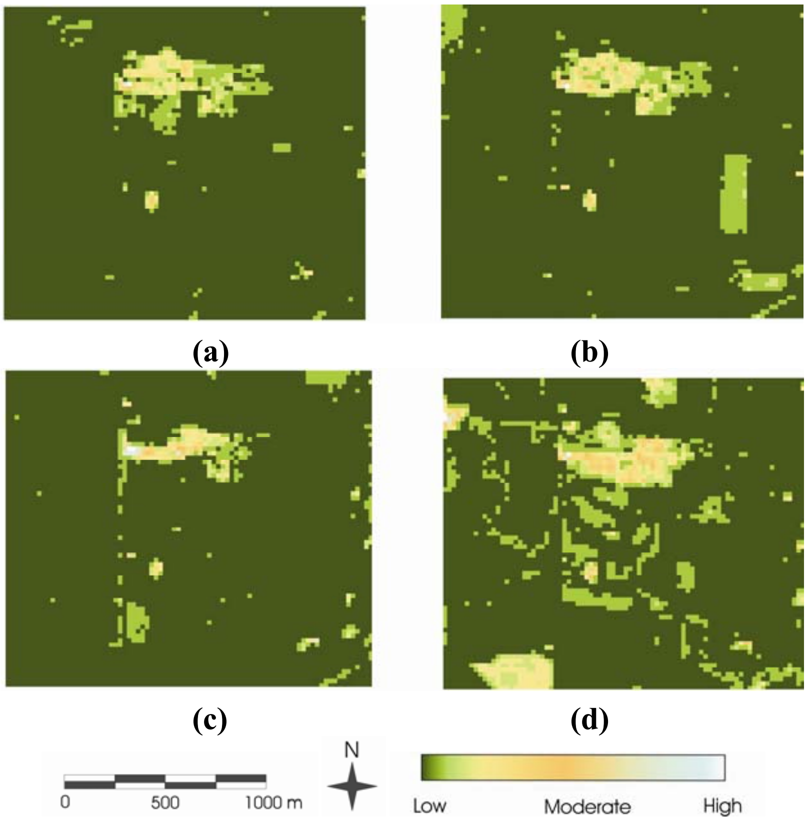
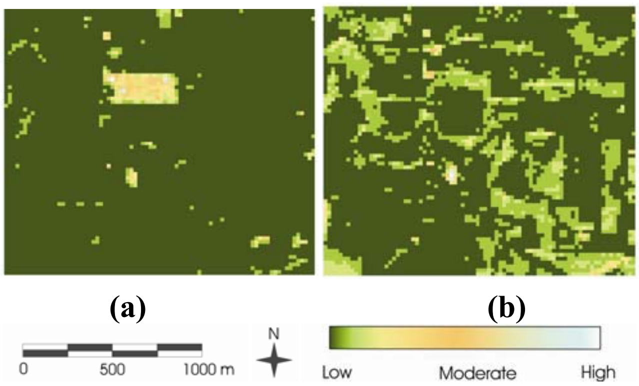


Figure 8. Characterization of surface vegetation anomaly patterns; **(a)** 23 August 2007 and **(b)** 19 September 2009



5.3. Verification Testing

The objective of this study was to evaluate the feasibility of employing moderate resolution Landsat TM data for anomaly detection and site remediation monitoring. Evaluation utilizing remote sensed imagery typically implies an exercise in ground "truthing" where the products of analysis are compared against a standard assumed to explain the "correct" categorization. The nature of this study challenges traditional approaches to the ground truth question since both greenness and anomaly are relative concepts and typically explained in qualitative terms. However, in order to support the observations revealed by the time sequenced data and the suggested relationship between "on the ground" remediation activities and induced changes in environmental conditions, verification of derived information products is required. Approaching the ground truth problem from this direction focused on conducting a series of verification tests based a One-Way Analysis of Variance. The One-Way ANOVA compares the mean of one or more groups based on one independent variable (or factor). For the purposes of this study it was possible to indentify two general groups of pixels, those impacted by the disturbance and those that remained unaffected from aerial photography published in the Ohio EPA case study report. These conditions served as two groups, impacted and non-impacted, and land areas descriptive of those characteristics were sampled from the 18 September 1999 image following a random stratified sampling procedure to collect values of greenness and anomaly.

Following a conventional hypothesis testing design the null and alternate hypotheses were set accordingly as:

- ***Null:*** *There are no significant differences between impacted and non-impacted areas*
- ***Alternate***: *There is a significant difference between impacted and non-impacted areas*

The logic of employing ANOVA in this test is to calculate the mean of the observations within each group, then compare the variance among these means to the average variance within each group. Under the null hypothesis, that the observations in the different groups all have the same mean, the weighted among-group variance will be the same as the within-group variance. As the means get further apart, the variance among the means increases. For the present study if impacted and non-impact areas are significantly different at the 0.05 level of confidence, there is support for the inference that greenness and anomaly indentify these contrasts and as these contrasts subside, the degree of impact and declined or has been ameliorated.

The test statistic to determine significance is the ratio of the variance among means divided by the average variance within groups, or F. This statistic has a known distribution under the null hypothesis, so the probability of obtaining the observed F under the null hypothesis can be calculated. The shape of the F-distribution depends on two degrees of freedom, the degrees of freedom of the numerator (among-group variance) and degrees of freedom of the denominator (within-group variance). The among-group degrees of freedom is the number of groups minus one. The within-groups degrees of freedom is the total number of observations, minus the number of groups. The results of the ANOVA for the greenness verification are presented in Table 3, while the ANOVA results for anomaly detection are given in Table 4.

Table 3. ANOVA Results for Greenness Verification.

Variable	**Impacted**		**Non-impacted**	
Mean	−0.386		31.39	
Variance	233.77		99.26	
Stand. Dev.	15.28		9.96	
ANOVA Results	**Sum of Sqrs**	**df**	**F**	**p**
Between Groups	15,146.3	1	90.9	0.000
Within Groups	9,657.9	58		
Levene's test for homogeneity of variance based on means: p = 0.014				

Table 4. ANOVA Results for Anomaly Verification.

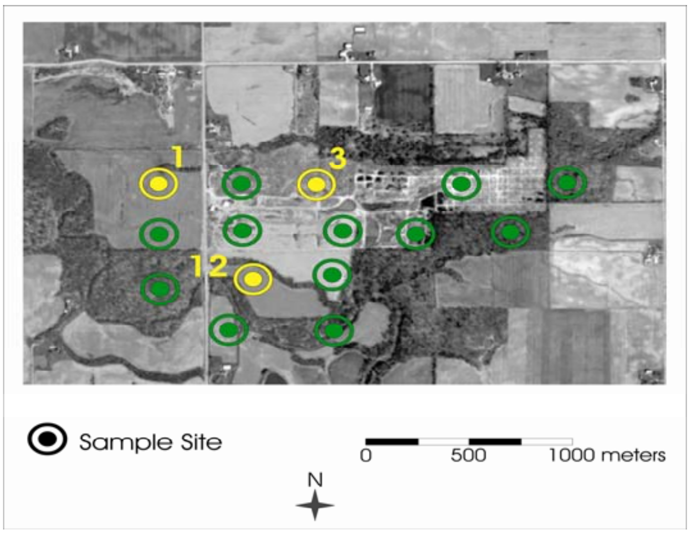
Variable	Impacted		Non-impacted	
Mean	36.16		1.21	
Variance	1,613.4		1.353	
Stand. Dev.	40.16		1.16	
ANOVA Results	**Sum of Sqrs**	**df**	**F**	**p**
Between Groups	18,263.5	1	22.62	0.000
Within Groups	46,829.9	58		
Levene's test for homogeneity of variance based on means: p = 0.000				

As evidenced in Tables 3 and 4, there is a significant difference ($p < 0.05$) between impacted and non-impacted areas based on both greenness and anomaly measurements. These results are instructive in two respects. First, they support the use of greenness and anomaly as a means of detecting contrasts in site conditions indicative of environmental damage. Secondly, because they capture differences between impacted and non-impacted areas, their application in a monitoring role creates two indices that can effectively track site-specific remediation progress.

5.4. Site Sampling

A series of sample points were taken from the sub-image data set and used to examine site-specific variations in the pattern of greenness and anomaly response over the study area. A systematic sample of 15 locations were chosen for analysis and used to construct greenness and anomaly profiles over time (Figure 9). The linear trend lines displayed in red were calculated using the Idrisi Taiga geographic analysis system (www.clarklabs.org). The profiles represent a series of best-fit estimates from linear regression and are used in this example simply to illustrate the direction of the trajectory remediation exhibits for each sample location.

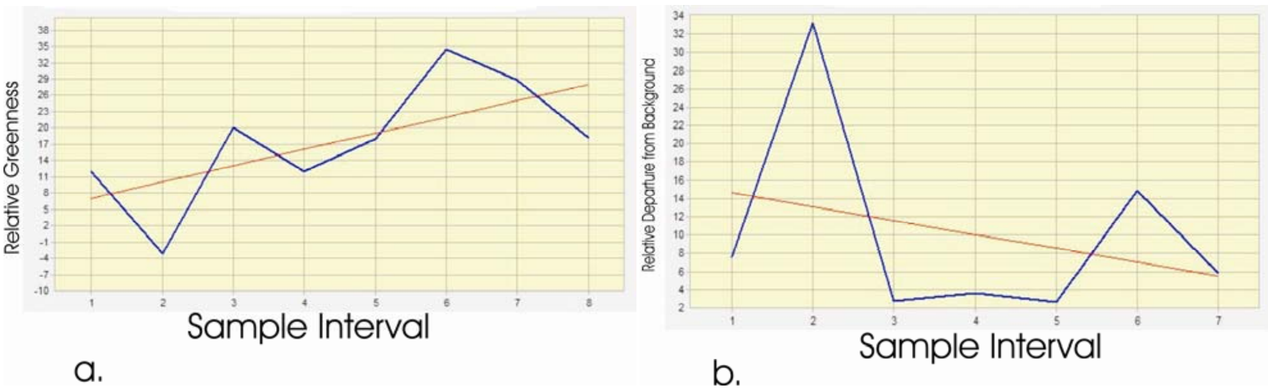
Figure 9. Location of sample points used in analysis.



The findings for a selection of three representative sites out of the total 15 sample points are discussed below.

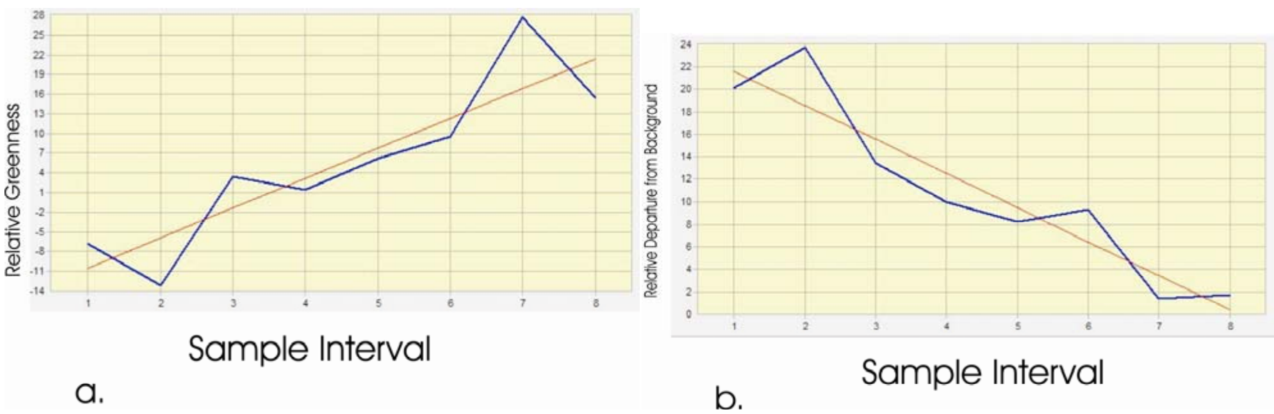
- **Sample Location 1:** This sample was taken approximately 200 m west of the tire recycling facility. The greenness profile for this location, as illustrated in Figure 10(a), explains a steep decline in greenness following the event (Sample Interval 2) and a sharp rise in greenness over time, leveling off to a condition above its pre-event state. The trend for this site is a steady upward trajectory of improvement. The anomaly profile for this sample location demonstrates greater conformity as the presence of aberrant pixels subsides. The two peaks in pattern suggest departures that corresponding to a loss of vegetative cover or vigor in 2001 and again in 2006 and 2007 (Figure 10(b)).

Figure 10. Greenness **(a)** and Anomaly **(b)** profiles for Sample #1 covering anniversary dates from 1998 through 2009 with x-axis not to scale.



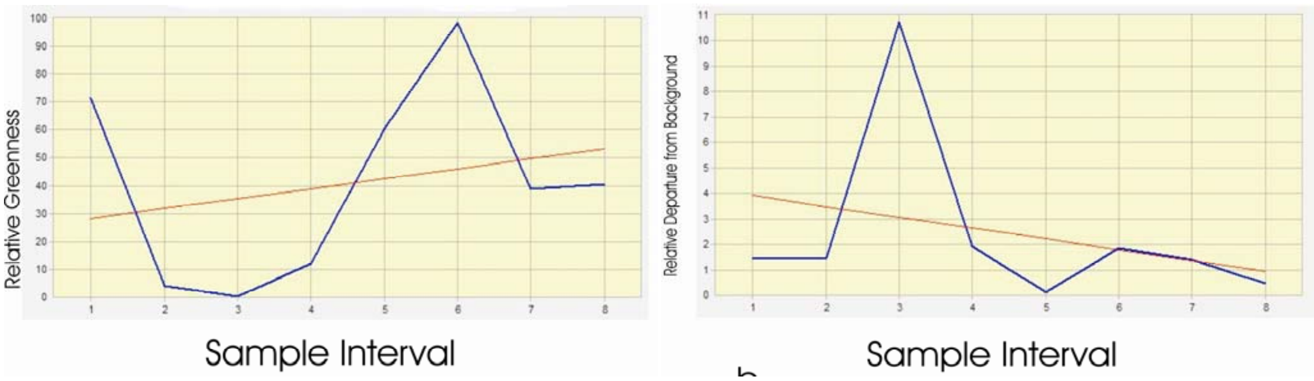
- **Sample Location 3:** This sample was taken approximately 200 m inside the boundaries of the tire recycling facility. This site illustrates site rehabilitation activities, where greenness, due to the abundance of automotive tires began below expected conditions and climbed steadily upward as remediate and restoration efforts modified site conditions (Figure 11(a)). The sharp upward trajectory in greenness provides evidence of significant site improvement. Supporting this conclusion is the contrasting pattern of anomalous conditions shown in Figure 11(b). The opposite trending suggests that site conditions improve; greater uniformity within the landscape can be observed.

Figure 11. Greenness **(a)** and Anomaly **(b)** profiles for Sample #3 covering anniversary dates from 1998 through 2009 with x-axis not to scale.



- **Sample Site 12:** The sample was taken approximately 200 m south between the tire recycling facility and the Sycamore Creek riparian corridor. During pre-disturbance conditions, the greenness index of this site was the highest of all samples taken and evidenced a steepest decline across immediate the post-disturbance sequence (Figure 12(a)). Recovery at this sample location was rapid beginning in 2003 (Sample Intervals 3–5), peaking in 2006 (Sample Interval 6) before leveling to a condition of improvement below its initial state. Aberrant conditions at this location displayed a strong anomaly in 2001 and a secondary peak in 2006; however the overall abnormality trend was downward across the period suggesting gradual improvement in environmental conditions (Figure 12(b)).

Figure 12. Greenness **(a)** and Anomaly **(b)** profiles for Sample #12 covering anniversary dates from 1998 through 2009 with x-axis not to scale.



(a) **(b)**

6. Discussion

Repair and removal are two assessment targets that environmental compliance and site remediation share in common. Facilities subject to compliance review or remediation are typically defined by materials that present sufficient risk to environmental quality such that their inadequate treatment or improper management violates health and safety standards. As inspection moves toward satellite-based strategies successful evaluation hinges on the ability of sensor technology to (1) identify and verify the removal of offending materials and (2) that site conditions have been returned to an environmentally neutral (sustainable) state. In this study moderate resolution satellite imagery focused on a major environmental calamity involving a facility with a history of environmental violations that had not been appropriately resolved. The moderate resolution data acquired from the Landsat 5 Thematic Mapper was employed to demonstrate how an annual inspection program of the north-central Ohio site could have been implemented based on the application of widely used vegetation indices coupled with an algorithm designed to identify anomalous patterns of surface reflectance. The greenness index produced from the Tasseled Cap transform was found to be extremely useful for three critical compliance activities:

(1) Documenting the systematic removal of offending materials (tires) from the site,
(2) Reviewing ground leveling and soil applications procedures used rehabilitate ground contaminants, and

(3) Tracking the establishment of vegetative cover at the site.

Review and examination of the environment surrounding the facility was also assisted by using the greenness index. Deviations in greenness identified off-site environmental impacts that could be attributed to the flow of contaminated runoff from the facility as well has short-term land use changes that were induced as a response to soil contamination an related effects. Additionally, the return of productive vegetation off-site was also detected which enables monitoring and assessment of the wider scope of "clean-up" operations. At each step in the time sequence of imagery managers are provided a synoptic view of the affected area that highlights locations of remediation success as well are locations where lingering adverse impacts remain. Using this information resources can be more efficiently allocated to those areas where needs are greatest and the overall performance of the site remediation program can be reviewed.

The success of resource management efforts is perhaps better understood from the anomaly detection data. The anomaly surface indentifies pixels that are "out of place" when compared to their neighbors. When examined on an annual basis they reveal locations on the ground that do not conform to the expected condition defined by the combined pattern of brightness, greenness and wetness as expressed by the Tasseled Cap Transform. Areas displaying anomalies can be assumed to require more direct management. Further, the anomaly data provides useful evidence regarding the local status of site remediation and irregularities that persist in the landscape. This can be noted in the pattern exhibited by the tire recycling facility as its "outlier" status contracts and eventually dissipates into the "normal" background descriptive of the scene. The return to normal and face validity of the methodology developed in this study is explained by examination of the site-specific samples extracted from the imagery. Each profile illustrates a general trend of improving environmental conditions and a reduction in aberrant pixels indicative of successful remediation following the calamity.

8. Conclusions

In this paper a remote sensing solution to the problem of site remediation and environmental compliance assessment was introduced. Employing the RDX anomaly-detection algorithm with vegetation indices developed from the Tasseled Cap Transform, the annual progress of a nine year remediation program following a significant environmental calamity was examined. Through the use of standard vegetation transform integrated into the anomaly detection strategy, a time-sequenced tracking of site remediation progress permitted both the identification of "off-site" impacts related to the calamity and progression of on-going "clean-up" operations. As demonstrated in this paper, standard vegetation transforms integrated into an anomaly detection strategy produced information products that communicated curious, conspicuous, and unanticipated patterns related to the Kirby fire event that could be used to guide compliance evaluation and remediation assessment; particularly those aspects that exhibited a discernable spatial expression. Although the 30 m resolution common to Landsat imagery has well recognized spatial and radiometric limitations, the examples provided in this paper should encourage the wider use of moderate resolution remotely sensed data for synoptic-scale environmental review and assessment programs.

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